REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
1. REPORT DATE (*DD-MM-YYYY*) 30-12-2005	2. REPORT TYPE Final	3. DATES COVERED (*From – To*) 1 September 2001 – 1 October 2005	
4. TITLE AND SUBTITLE Shear-Layer along a Perforated Surface, Large and Small-Scale Instabilities		5a. CONTRACT NUMBER	
		5b. GRANT NUMBER N00014-01-1-0606	
		5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Rockwell, Donald		5d. PROJECT NUMBER	
		5e. TASK NUMBER	
		5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lehigh University, Department of Mechanical Engineering and Mechanics, 354 Packard Laboratory, 19 Memorial Drive West, Bethlehem, PA 18015			8. PERFORMING ORGANIZATION REPORT NUMBER 533620
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research, Code 333, Mechanics Division, Ballson Center Tower One, 800 North Quincy Street, Arlington, VA 22217-5660			10. SPONSOR/MONITOR'S ACRONYM(S) ONR
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified			
13. SUPPLEMENTARY NOTES			

14. ABSTRACT

Shear flow past a perforated or slotted plate, with a cavity on its backside, can give rise to highly coherent, self-sustained oscillations. In fact, the coherence and magnitude of these oscillations can actually exceed those from the corresponding open cavity. The fundamental features of such oscillations are determined using a technique of high-image-density particle image velocimetry. A cinema version of this technique allows space-time representations of the flow structure. Global instantaneous and phase-averaged patterns are interpreted in conjunction with spectral and cross-spectral analysis of the unsteadiness on either side of the perforated or slotted plate. Using these approaches, a new type of instability has been defined. It is centered on development of a large-scale structure along the surface of the plate, in accord with the evolution of patterns of small-scale structures within each of the perforations or slots. By interpreting the phase shifts associated with the streamwise propagation of the disturbance on either side of the plate, relative to the phase shift of the unsteady volume flux through the plate, it is possible to arrive at a detailed physical model. This model is a generic one, valid for a range of perforated and slotted plate configurations. The consequences of the geometrical parameters of the plate, including the plate thickness and the scale of the individual perforations/perforations or slots, are shown to have a substantial influence. Furthermore, the detailed flow structure is interpreted in accord with the dimensionless frequency and amplitude of oscillation. Understanding of the basic flow physics leads to proposed concepts for attenuation of these oscillations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	UU		Donald Rockwell
UU	UU	UU			19b. TELEPHONE NUMBER 610-758-4107

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

20060103 096

SHEAR LAYER ALONG A PERFORATED SURFACE: LARGE- AND SMALL-SCALE INSTABILITIES

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Award Number: ONR Grant N00014-01-1-0606

ABSTRACT

Shear flow past a perforated or slotted plate, with a cavity on its backside, can give rise to highly coherent, self-sustained oscillations. In fact, the coherence and magnitude of these oscillations can actually exceed those from the corresponding open cavity. The fundamental features of such oscillations are determined using a technique of high-image-density particle image velocimetry. A cinema version of this technique allows space-time representations of the flow structure. Global instantaneous and phase-averaged patterns are interpreted in conjunction with spectral and cross-spectral analysis of the unsteadiness on either side of the perforated or slotted plate. Using these approaches, a new type of instability has been defined. It is centered on development of a large-scale structure along the surface of the plate, in accord with the evolution of patterns of small-scale structures within each of the perforations or slots. By interpreting the phase shifts associated with the streamwise propagation of the disturbance on either side of the plate, relative to the phase shift of the unsteady volume flux through the plate, it is possible to arrive at a detailed physical model. This model is a generic one, valid for a range of perforated and slotted plate configurations. The consequences of the geometrical parameters of the plate, including the plate thickness and the scale of the individual perforations/perforations or slots, are shown to have a substantial influence. Furthermore, the detailed flow structure is interpreted in accord with the dimensionless frequency and amplitude of oscillation. Understanding of the basic flow physics leads to proposed concepts for attenuation of these oscillations.

TECHNICAL SECTION

OVERVIEW AND MOTIVATION

Flow past surface discontinuities, in the form of cutouts or cavities, occurs in a wide variety of external and internal flows related to naval applications. The region of separated flow along the cavity can give rise to oscillations having pronounced coherence, and in the limiting case, generation of flow tones. Furthermore, even when such tones are not present, the development of turbulence along the cavity is associated with broadband noise generation. Certain of these cavity configurations involve perforated or slotted plates along the mouth of the cavity, in order to preclude existence of a fully separated flow in that region. The aim of the present investigation is to characterize the unsteady flow patterns due to turbulent shear flow past perforated and slotted plates.

OBJECTIVES AND APPROACHES

The overall objectives of this program are to:

(a) Determine the underlying physics of long wavelength instabilities due to shear flow past a perforated or slotted plate bounded by a cavity, in absence of any acoustic resonant or elastic wall effects, i.e., purely hydrodynamic oscillations.

(b) Characterize the basic features of long wavelength instabilities past perforated or slotted plates in presence of simulated acoustic resonance of the bounding cavity, and thereby the degree of coupling between the long wavelength instability along the plate and the resonant characteristics of the cavity.

(c) Develop and implement techniques of global characterization of the flow structure for both of the foregoing classes of oscillations, including wholefield spectral and cross-spectral techniques. The aim of these approaches is to provide the first insight into the phase and amplitude variations, as well as the instantaneous patterns of the flow structure, on both the front- and back-sides of the plate, which are associated with highly coherent oscillations.

This research program has involved three classes of experimental systems:

(a) *A perforated plate-cavity system* designed to preclude acoustic resonant and wall elasticity effects, such that purely hydrodynamic instabilities, or oscillations, occur. A fully-evolved turbulent inflow boundary layer of defined thickness is incident upon the perforated plate. The design of this system allows variation of both the hole diameter and thickness of the plate, while keeping the open area ratio constant. In addition, variations of the effective length of a given perforated plate are attainable using a translating impingement edge.

(b) *A slotted plate-cavity system*, similar to the perforated plate system of (a), allows determination of the oscillation characteristics arising from flow past an essentially

two-dimensional plate configuration. As for (a), emphasis is on the case of purely hydrodynamic oscillations.

(c) *A slotted plate/resonant cavity system* accounts for the effects of coupling between the aforementioned hydrodynamic instabilities of (b) and a simulated resonant acoustic mode of the cavity. This system involves a shallow water configuration, whereby the free-surface resonant mode of the bounding cavity stimulates either acoustic resonance within a rigid cavity or elastic wall motion of a flexible cavity.

For all of the foregoing experimental systems, methods of high-image-density particle image velocimetry have been implemented. Various orientations of laser sheets allow characterization of the quasi-two-dimensional flow structure on both the high-speed (front) side of the perforated or slotted plate, as well as on the back-side of the plate. Furthermore, other orientations of the laser sheet allow characterization of the spanwise structure of the instability. A cinema version of PIV is employed for all experiments, with the aim of characterizing the space-time evolution of the instabilities. This space-time imaging leads to global spectral and cross-spectral analysis over entire planes of the flow, including:

(a) *Spectral content* of oscillation: coexistence of, and transformation between, organized modes of oscillation.

(b) *Scaling of frequencies* of oscillation accounting for inflow in plate parameters.

(c) *Organized wave characteristics* on either side of the plate via global patterns of phase and amplitude of velocity and vorticity fluctuations.

(d) *Phase and amplitude distributions* of volume flux through the surface of the plate.

(e) *Overall phase shift along plate* as a criterion for the existence of an oscillation.

(f) *Local pressure fluctuations* in relation to fields of fluctuating velocity.

SUMMARY OF RECENT PROGRESS

The range of experimental investigations carried out during the course of this program has defined generic features of a new type of instability arising from flow past perforated and slotted plates. In the following, these features are briefly described.

ELEMENTS OF SELF-EXCITED INSTABILITIES

Downstream Propagating Instability

The downstream propagating instability involves the onset and development of a large-scale structure on the high speed side of the plate. Extensive imaging has shown that the form of this instability is remarkably similar for cases of both slotted and perforated plates and, for each of these classes of plates, for a significant range of geometrical parameters. The strength of this instability appears to be largest when the

geometrical parameters of the plate allow existence of well-defined, small-scale recirculation cells within the slots of a slotted plate; an analogous criterion is expected to hold for the case of the perforated plate. During evolution of the instability, however, these time-averaged recirculation cells undergo highly unsteady distortion and development. The basic features of the large-scale instability have been characterized in terms of patterns of vorticity and velocity.

In addition, in order to augment the foregoing characterization of the physical aspects of the instability, quantitative representations of its amplitude and phase on either side of the plate have been determined using an approach of global spectral and cross-spectral analysis. In essence, this approach involves acquisition of simultaneous time records of the velocity fluctuations at thousands of points over the flow domain and, with these records at hand, determination of the contours of constant amplitude of the spectral peak of the self-sustained oscillation, as well as contours of constant phase of the oscillation. Such phase contours allow determination of the propagation speed of the large-scale disturbance in the downstream direction. In addition, such phase contours can provide a valuable index of the "jitter" of the oscillation, i.e., the degree to which it shows a lack of phase coherence in regions where the amplitude is small, and the instability is insufficiently developed.

Consequence of Downstream Propagating Instability along Backside of Plate

The large-scale instability described in the foregoing has important consequences for the flow patterns along the backside of the plate. The sequential dynamic development of small-scale recirculation cells along the plate, in accord with propagation of the instability, involves periodic ejection of fluid from the slot or perforation to the backside region of the plate. This ejected fluid is in the upstream direction. The time-averaged consequence of this ejection process is a counterflow along the backside of the plate, which has the overall form of a wall jet. In fact, the magnitude of the velocity of this counterflow is directly related to the overall strength of the self-sustained oscillation. The existence of this counterflow has important consequences for successful implementation of attenuation techniques.

Distortion of Downstream Propagating Instability at Trailing-Edge of Plate

When the downstream propagating instability interacts with the trailing-edge of the plate, i.e., the streamwise location at which the slotted or perforated plate ceases to exist, a violent, highly coherent pattern of unsteadiness occurs. It involves a pulsating jet flow through the last slot(s) or perforation(s) near the trailing-edge. This pulsating jet effect is analogous to the distortion of large-scale concentrations of vorticity occurring for the case of an open cavity in absence of a perforated or slotted plate. In both scenarios, this trailing-edge region serves as a powerful source of upstream influence, which allows maintenance of highly coherent, self-sustained oscillations.

Influence of Plate Thickness on Instability

The large-scale instability along the surface of the plate, and the small-scale instabilities associated with development of recirculating flow pattern within each of the

slots or perforations, can occur over a relatively wide range of plate thickness. It has been demonstrated that, irrespective of whether one considers a slotted or perforated plate, a given value of thickness exists for which the self-sustained oscillation has its maximum amplitude. For values of thickness either larger or smaller than this optimal thickness, the amplitude of the oscillation is substantially attenuated.

Furthermore, scaling of the dimensionless frequency of oscillation has been formulated for both slotted and perforated plates. The scaled, dimensionless frequency is shown to have a very similar form as the plate thickness is varied.

The underlying physics associated with the foregoing trends has been interpreted in terms of patterns of phase-averaged velocity vectors, contours of constant vertical velocity, and contours of constant vorticity. Using these approaches, the definitive mechanisms associated with the amplitude of oscillation have been defined.

Influence of Scale of Gap or Perforate on Downstream Propagating Instability

As indicated in the foregoing, the central feature of highly coherent, self-sustained oscillation is the onset and development of small-scale structures within the slots or perforations of the plate. It has been determined that when the effective scale of the slot or perforate becomes sufficiently large, such small-scale structures can no longer exist, and, as a consequence, the instability is attenuated. Detailed characterization of the quantitative flow structure on either side of, and within, the slots of the slotted plate show that when the scale (width) of the slot becomes sufficiently large, separated shear layers form from the leading- edges of each of the slats of the slotted plate. The existence of these separated layers involves a region of significant turbulence intensity, which may be related to broadband noise generation. All of the foregoing features have been characterized in terms of patterns of phase-averaged velocity and vorticity.

Resonant-Coupling of Downstream Propagating Instability with Mode of Adjacent Cavity

The self-excited, downstream propagating instability described in the foregoing occurs in absence of any acoustic resonant or hydroelastic effects. That is, it is an inherent, purely hydrodynamic instability. If, however, this instability occurs in presence of a bounding cavity, and the frequency is such that the instability couples with either an acoustic, Helmholtz, or elastic wall mode of the cavity, the amplitude of the oscillation may be substantially enhanced.

The occurrence of such a resonant-coupled instability has been characterized using a unique free-surface simulation of the free-surface (gravity wave) resonant modes of the bounding cavity. It has been demonstrated that the overall response of the system, i.e., the onset and existence of coupled interaction between the inherent instability along the slotted plate and the cavity resonant mode, exhibit a well-defined behavior.

The physical features of this oscillation have been characterized in terms of phase-averaged and time-averaged patterns of velocity vectors, vorticity, and Reynolds stress. In addition, the spectral and cross-spectral characteristics of the velocity field on

either side of the slotted plate, as well as within the slots, have been determined using the aforementioned technique of spectral and cross-spectral analysis. These approaches also lead to a clear delineation of the concept of lock-on of the inherent instability to the resonant mode of the cavity. Remarkably, the overall features of the lock-in process are very similar for cases without and with a slotted plate along the opening of the cavity.

ATTENUATION CONCEPTS FOR INSTABILITIES

Preliminary investigation into potential techniques for attenuation of the inherent hydrodynamic instability described in the foregoing have been undertaken for both perforated and slotted plates. These initial studies, which have addressed deployment of vortex generators along the leading-edge of a perforated plate, as well as geometrical devices along the backside of the plate, suggest that significant attenuation can be achieved with either of these approaches. From the standpoint of minimization of the broadband noise, it is likely that the so-called class of backside attenuation techniques should be most productive.

TECHNOLOGY TRANSFER

During the course of this research program, substantial interaction has been developed with colleagues in Navy laboratories, as well as with engineers at ship building facilities. These interactions have provided a practical focus for the ongoing investigation. The research results of this program are available in the archival literature, for use by all concerned with instabilities associated with shear flow along slotted and perforated plates. In addition to Naval applications, design of automobile muffler systems, as well as liners for rockets in the aerospace industry, are representative applications that will benefit form the present program.

Contacts and communication with the following have been pursued during the course of this program.

(i) NSWC (Carderock): Ted Farabee and Paul Zoccola.

(ii) NUWC (Newport): Steve Jordan

(iii) Electric Boat: Brent Paul

(iv) Northrup Grumman Newport News: Kevin Smith

(v) Electric Boat: Chris Hoddinot

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4. "Self-Excited Oscillations of Flow Past a Perforated Plate: Attenuation via Three-Dimensional Surface Elements", Journal of Fluids Engineering, 2004, Vol. 127, No. 1, pp. 151-164 [Ozalp, C., Pinarbasi, A., and Rockwell, D.].

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6. "Self-Sustained Oscillations of the Shear Flow Past a Slotted Plate Coupled with Cavity Resonance", Journal of Fluids and Structures, 2003, Vol. 17, Issue 8, July, pp. 1237-1245. [Ekmekci, A. and Rockwell, D.]

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8. "Oscillation of Shallow Flow Past a Cavity: Resonant Coupling with a Gravity Wave", in preparation [Ekmekci, A. and Rockwell, D.]

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10. "Shallow Cavity Flow Tone Experiments: Onset of Locked-On States", Journal of Fluids and Structures, 2003, Vol. 17, Issue 3, March, pp. 381-414 [Lin, J.-C., Oshkai, P., Reiss, M., Pollack, M. and Rockwell, D.].

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14. "Imaging of Acoustically Coupled Oscillations Due to Flow Past a Shallow Cavity: Effect of Cavity Length Scale", Journal of Fluids and Structures, 2005, Vol. 20, No. 2, February, pp. 277-308 [Oshkai, P., Geveci, M., Pollack, M. and Rockwell, D.].

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Flow-Induced Vibrations: An Engineering Guide, Dover Press, 2005 [Naudascher, E. and Rockwell, D.]

TECHNICAL REPORTS

0

PRESENTATIONS

0

PATENTS

0

HONORS/AWARDS/PRIZES

The principal investigator, Donald Rockwell, is the Paul B. Reinhold Professor of Mechanical Engineering at Lehigh University. He received the Lehigh Engineering Ingenuity Award for a Distinguished Faculty Member in May, 2004.

Dr. Rockwell has received the following awards: Alexander von Humboldt Fellowship (Germany, 1974-1976); Overseas Fellow of Churchill College, Cambridge University (elected 1981); Paul B. Reinhold Professor, Lehigh University (1988 to present); Eleanor and Joseph Libsch Research Award, Lehigh University (1989); Fellow of American Physical Society (1993); Fellowship Committee (1996-1997) and Fluid Dynamics Prize Committee (1997-1998) of Division of Fluid Dynamics, American Physical Society; Müller Prize Lectures (Karlsruhe, Germany 1998).

OTHER SPONSORED WORKS

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Location: Lehigh University
Effort: 0.6 Mo S/Yr (CS 1.0 Mo AY/Yr)

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Agency: Arrow International, Inc.
Amount: $260,747
Period: 3/15/2005 – 3/14/2006
Effort: 1.2 Mos AY/Yr

Title: Fluid-Acoustic Coupling: Review And Analysis
Agency: DoE-Knolls Atomic Power Laboratory
Amount: $37,520
Period: 12/6/2004 – 9/30/2006
Effort: 1.0 Mo AYf/Yr

Title: Origin and Control of the Flow Structure on Unmanned Combat Air Vehicles
Agency: DoD-Air Force-Office of Scientific Research
Amount: $316,978
Period: 1/1/2005 – 12/31/2007
Effort: 1.0 Mo S/Yr

Title: Flow Past Obstacles in Shallow Water: Wake Structure and Free-Surface Deformation
Agency: NSF-Directorate for Engineering
Amount: $268,562
Period: 5/1/2003 – 4/30/2007
Effort: 0.5 Mo Ay/Yr

Title: Wake Structure, Loading and Vibration of Cylinders: Effects of Surface Nonuniformities and Unsteady Flow
Agency: DoD-Navy-Chicago
Amount: $1,293,098
Period: 12/1/1993 – 11/30/2006
Effort: 1.0 Mo S/Yr

Title: Shear-Layer along a Perforated Surface, Large and Small-Scale Instabilities
Agency: DoD-Navy-Chicago
Amount: $403,886
Period: 9/1/2001 – 10/1/2005
Effort: None

PENDING SUPPORT

Title: Universal Wind Tunnel Facility for Aerospace Engineering Minor within the Department of Mechanical Engineering and Mechanics
Agency: NSF-Directorate for Education and Human Resources
Amount: $50,000
Period: 12/1/2005 – 11/30/2007
Effort: No Support

Title: Space-Time Imaging System
Agency: DoD DURIP
Amount: $165,690
Period: 04/01/2006- 03/31/2007
Effort: No Support

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